THE RECONSTRUCTION OF THE ASSEMBLAGE OF MINERAL DEPOSITS OF THE MOON

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This paper is based on the interpretation of recent rocket photography of the Moon, and on certain comparisons and extrapolations made on the basis of the properties and theories of genesis of terrestrial deposits which are described in up-to-date textbooks and review articles of Economic Geology (see, for example, 1, 2, 3). Interpretation of rocket photographs from the Moon have led the writer to the conclusion (4) that it is unlikely that a high proportion of the meteorites known from collections are derived from the Moon. The theory of asteroidal origin seems to be more probable. It appears that the mineral deposit pattern of a given celestial body may depend on its mass, and it is, therefore, a possibility that the mineral deposit pattern for the Moon is in many respects intermediate between that of the Earth and that indicated for the asteroid sized bodies (smaller than the Moon) from which the meteorites may be derived.

The main aim of this paper is an assessment of our power to reconstruct, on the basis of indirect evidence, the mineral deposit assemblage of a given celestial body. This assessment may be tested in the near future in the course of manned lunar landings and explorations. Each genetical class of mineral deposits which might be expected to be found is briefly considered in the following paragraphs (numbered 1-6).

1. Magmatic segregates

The gravitational segregation of deposits of refractory minerals from the molten igneous rocks within the Earth's crust is a relatively rare phenomenon. This rarity may explain the lack of any magmatic segregate-type material among the small number of the meteorites which crystallized from a melt, namely the Achondrites. In view of the low albedo, and therefore probably basic character of much lunar rock, magmatic segregate-type deposits of magnetite, pyrite, and chromite in particular are likely, and the prospects of finding high grade deposits of these minerals would seem to be good. However, the lack of dissected major intrusions because of lower rate of erosion, the less intensive tectonics, and the lower gravitational field of the Moon may be factors adverse to the formation of gravitational segregates. For these reasons outcrops of high pressure, high temperature diamond deposits of the terrestrial Kimberley type, are unlikely to be found. There is an intriguing probability of lunar, effusive, lava-flow-type magmatic segregates. The existence of this type of deposit has not been conclusively proved on Earth, although hitherto unpublished work of the writer would seem to indicate this genesis for the haematite-magnetite occurrences of El Laco, Northern Chile. It would seem likely that on the Moon there would be increased chances of encountering such effusive, magmatic, segregates for the following reasons: a) there is presumably a greater abundance of basic rocks which contain the highest

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proportion of the refractory minerals, and b) according to the interpretation of lunar photography in general, there are a far greater number of individual lava flows preserved on the Moon than on the Earth.

2. Fumarole deposits

The abundance of fumarole and hydrothermal products on the surface of the Moon would primarily depend on the ratio between the number of craters produced by impact and volcanism, because only volcanism would substantially contribute toward the accumulation of magmatic, volatile-condensation products. On Earth today the ratio volume of impact/volume of volcanic rocks is in the order of 10^{-8} or less. The lower intensity of volcanic activity due to smaller mass on the one hand, and the preservation of archaic impact craters on the other hand, may drastically increase the impactite/volcanite ratio on the Moon. In the opinion of the writer, however, it would seem to be unlikely that these factors would be responsible for an increase in the ratio of eight orders of magnitude, bringing the ratio in question to unity. It would therefore seem likely that the surface of the Moon is rich in fumarole products.

A full discussion of the problem of interpretation of lunar craters (5) is outside the scope of this paper. It should be stressed, however, that most of the terrestrial craters show positive mean elevation, because lava has been added from deep sources in the course of volcanic activity. The rare maar-type crater of Nilalhue, Southern Chile, has zero mean elevation (6), because in that case all the ejecta were produced through gas explosions. The few known or inferred impact craters on Earth also reveal zero mean elevation, because under the usual impact velocities, the volume of the impacting object is negligible, when compared to the volume of rock displaced by the impact. Craters and domes of well-defined positive elevation appear on wide angle frame 213 of Orbiter (November 25, 1966), and this fact strongly supports the volcanic origin of at least some of the lunar craters.

On the Earth, the fumarole deposits are of more or less transitional character because the sulphur of such deposits becomes oxidized in the atmosphere, and most of the saline condensates are washed away with the precipitations into the oceans or desertic basins. Much of the Mg^{++} and K^{+} of these exhalation products of the Earth become reabsorbed on the floors of the oceans, and the evaporites, which form in the course of the drying-out of the marine lagoons are relatively depleted of these metals, and are therefore enriched in the salts of Na and Ca which are not so readily absorbed.

On the Moon, there is no atmospheric transport, and therefore the resulting "fumarole-evaporite" type deposits would preserve their original contents of Mg. Other factors which may contribute to a relatively high percentage of Mg salts of these lunar deposits would be the alkali-poor, basic character of the lunar magma, further the elimination of free sulphur, and possibly also alkalies through solar radiation and wind particularly within the older deposits.

The foregoing considerations lead us to the prediction that the surface of the Moon would be exceptionally rich in fumarole-evaporite type deposits, and that the volume of these would be comparable (after making allowance for the smaller surface and lower rate of erosion on the Moon) to the total volume of the salts, etc. which are concentrated within the terrestrial evaporites, oceans, and fumaroles. Such deposits (which may reach masses in the order of several hundred million tons) would have a solar radiation, and wind-evaporated, surface zone in which MgO, $MgSO_4$, $MgCO_3$, $MgCl_2$, etc. and some Fe and Ca salts would be intermixed with volcanic ejecta, meteorites, and cosmic dust. There is a possibility that with increasing depth in such deposits, the percentage of the relatively more volatile alkali salts, sulphur, and hydrocarbons would tend to increase.

It is interesting to note that Kuiper (7) interpreted the white, snow-like substance on the peak of the Alphonsus crater (shown on Ranger VII photographs) as a fumarole product which traversed a tuff-like material of pyroclastics, and he compared this with a white mixture of gypsum and calcium oxide which covered the slopes of Laimanca Volcano, Hawaii, after an eruption. The Orgueil and other type I carbonaceous chondrites show considerable petrological similarities to fumarole-product impregnated terrestrial tuffs (8). The approximately 15% of $MgSO_4$ which is present in these stones is significant in view of the foregoing considerations, and furnishes further indications that salts of Mg may be expected as major constituents of the lunar deposits.

3. Hydrothermal deposits

The lunar pegmatites are expected to be mainly of basic type, as it is likely that the Moon, because of its low gravitational field, did not segregate a granitic continental crust. This would favor pegmatites enriched in Rare Earths, Zr, P, Th, etc., but the economically more important terrestrial Li, Be, B, V, etc., pegmatites associated with granites may be absent or very subordinate.

As regards the relatively lower temperature, relatively deep-seated, hydrothermal deposits, the Moon is expected to be essentially an oceanic-type mineralogical province. This means that the mineral veins may contain volatile condensates characteristic of the terrestrial basic rocks, namely Cu and Fe. Deposits of Hg. Bi, Sb, Au, Pb, Zn, As, Ba, and P are associated with all the terrestrial igneous rocks and they may, therefore, be present in relatively smaller quantities on the Moon. The typical granitic volatiles, that is, Mo, W, U, Sn, and F, may, however, be practically absent.

Lack of deep erosion may render the hydrothermal deposits of deep-seated origin relatively rare, and the exposure of close-to-surface types more common. These latter contain the sulphides of the heavy metals and some elementary sulphur. Such deposits in question might have little or no thermal zoning, and would have a simple mineralogy of impure ores and gangues, because their cooling and crystallization occurred too rapidly to produce large and well-formed crystals of their minor constituents (see heading 2).

On account of the close-to-surface character of most of the deposits, there would appear to be good prospects for the presence of As, Sb, Hg, and B. It would seem likely that solar radiation and wind would cause the formation of a surface zone which is depleted in the hydrothermal minerals of extreme volatility, such as yellow S and red HgS and As_2S_3. This possible scarcity of colored minerals may render difficult the visual detection of hydrothermal deposits from colored photographs, or black and white photographs made through different filters. On the photographs made by Rangers 7, 8, and 9, numerous (up to several kilometers long) lodes appear, most of which are of lighter shade than the surrounding ground. The light color favors the possibility of fissure fillings of close-to-surface, fumarole-type composition, such as earth-alkali and alkali salts with sulphur. The presence of gaping fissures on other photographs may be accounted for either by displacements without the ascent of condensable volatiles (as this occurs in case of the non-mineralized faults of the Earth) or the preferential erosion of highly volatile material, possibly S, hydrocarbons, etc. , which filled the fissures.

It was proposed by the writer (8), on the basis of comparative petrographical and chemical studies, that the carbonaceous chondrites in general closely resemble terrestrial pyroclastics impregnated with hydrothermal products, and in the type I stones, features suggestive of terrestrial fumarole conditions appear as well. According to the computation of data from the up-to-date literature, the redistribution ratios, that is, ppm in carbonaceous chondrites ÷ ppm in mean chondrites of some of the hitherto determined minor elements are as follows:

Hg	220	Cu	2, 5
Bi	52	V	1, 9
C	19	S	1, 7
Pb	17	Rare Earths	1, 6
Ag	16	U	1, 1
Zn	3, 9		

The statistical work of the writer on the terrestrial hydrothermal deposits, which is at present in progress, indicates that, by-and-large, the above redistribution ratios are very similar, even in numerical details, to those between the mean of hydrothermal veins in the terrestrial oceanic provinces and that of the Earth's crust. The only really significant difference is the higher value for S and the lower value for C in the terrestrial hydrothermal deposits. Such difference may be explained by the possibility that under the relatively oxidizing conditions within the crust of a comparatively smaller celestial body, the S would escape in the free state, and the C would tend to persist as graphite, amorphous C, and higher molecular organic substances. Under the relatively more reducing conditions which prevail within the crust of an Earth-sized body, the carbon tends to escape as low molecular hydrocarbons, and a higher proportion of sulphur would be retained as sulphides of iron and other heavy metals. We may therefore expect that the mean S/C ratio of the lunar hydrothermal deposits would be lower than the value of approximately 10 for the Earth, but higher than that of 1.5 for the carbonaceous meteorites.

4. Sedimentary and metamorphic deposits

No sign of sediment or metamorphosed sediment has been detected among the approximately 2000 meteorites in our hands, and it would seem unlikely that a relatively small celestial body would retain atmosphere and hydrosphere for sufficient time for the production of appreciable amounts of sediments. The absence of clear indications of sedimentary rocks on the hitherto published rocket photographs of the Moon would seem to point to the possibility that mineral deposits of sedimentary origin may be absent or very subordinate on the Moon. These include secondary concentrations of resistant minerals such as Au, Pt metals, minerals of Zr, Th, Rare Earth, Fe, etc.; sands, clays, bauxite, limestone, dolomite, chert, phosphorite, garnet, corundum, etc.

5. Carbonaceous deposits

As discussed at the termination of the foregoing paragraph 3, it appears that the Moon may have a higher overall C percentage in its crust than the Earth has. The reconstruction of the mode of distribution and chemistry of the lunar carbosphere is a difficult task because the relative importance of several factors, to be discussed in this paragraph, is not readily assessable.

The writer has suggested (9) that an increase in the mean O/H and a decrease in the H/C of the carbonaceous complex, with decreasing mass of a given celestial body, may be expected. The presence of organisms of terrestrial biochemistry would have the effect of increasing the overall percentage of organic carbon and increasing the H/C. As the presence of abundant life on the Moon seems unlikely at any stage of its history, it seems probable that the Moon's carbosphere may be of higher overall percentage but more carbonized (mainly as graphite and graphitite) than that of the Earth. The highly aromatic and oxygenated nature of the mean lunar abioliths makes unlikely the possibility of tar-like hydrocarbon filled craters, as envisaged by Wilson (10).

On Earth, the concentration of the carbonaceous complex into relatively pure and extensive deposits of coals, etc. was principally caused through the abundance of living organisms. With the absence or more subordinate character of this biological factor on the Moon, there may be fewer high grade organic deposits, although this trend may be partially or wholly counterbalanced by the higher overall percentage of carbonaceous matter, and therefore the improved probabilities of the occasional concentration of carbonaceous matter through hydrothermal and volcanic processes. It is possible that the individual deposits may have an evaporated or carbonized surface zone, which would be underlain by a zone which is enriched with the products of distillation along the surface and which would also show a maximum in H/C.

Photographs from Surveyor spacecraft indicate that the lunar matter which was disturbed through the impact of one of the legs of the spacecraft was of darker shade than the undisturbed powdery matter. This would seem to indicate either the eflorescences of salts on the surface or the leaching-out of dark carbonaceous material from the surface through solar radiation. The second alternative would imply a lunar carbonaceous complex, which may originate from lunar dust, cosmic dust, and carbonaceous meteorites.

8 Impactites

Because of the lack of an appreciable atmosphere, the "impactites" on the surface of the Moon would be certainly of greater importance than on the Earth (see paragraph 2). The abundance of nickel-iron present on the lunar surface is difficult to assess, but it may prove to be considerable. It is possible that secondary volcanism, following the impact of larger bodies, may bring to the surface some of the nickel-iron from deeply buried impactites. As the impact on the Moon would liberate a considerable density of energy, the presence of new high pressure forms of minerals may be likely. It was mentioned under paragraph 1 that the crust of the Moon may not contain deposits of diamonds, but the meteoritic debris on its surface may prove a considerable source of industrial diamonds. In this connection it may be noted that the impact-shocked Canon Diablo siderites contain an average of some 0.1% of diamonds, which represent an approximately 10,000-fold higher concentration than in the richest hitherto known terrestrial deposits from South Africa.

It may be concluded that the systematic study of mineral deposits on the Moon would yield, in the foreseeable future, data of general theoretical interest regarding the processes of crystallization of magmas under gravitational fields of differing intensities, and the comparison of redistribution of volatiles within celestrial bodies of the mass of the Moon and the mass of the Earth, respectively. The effects of differing types of atmospheres and radiations on the close-to-surface zones of mineral deposits could be studied as well.

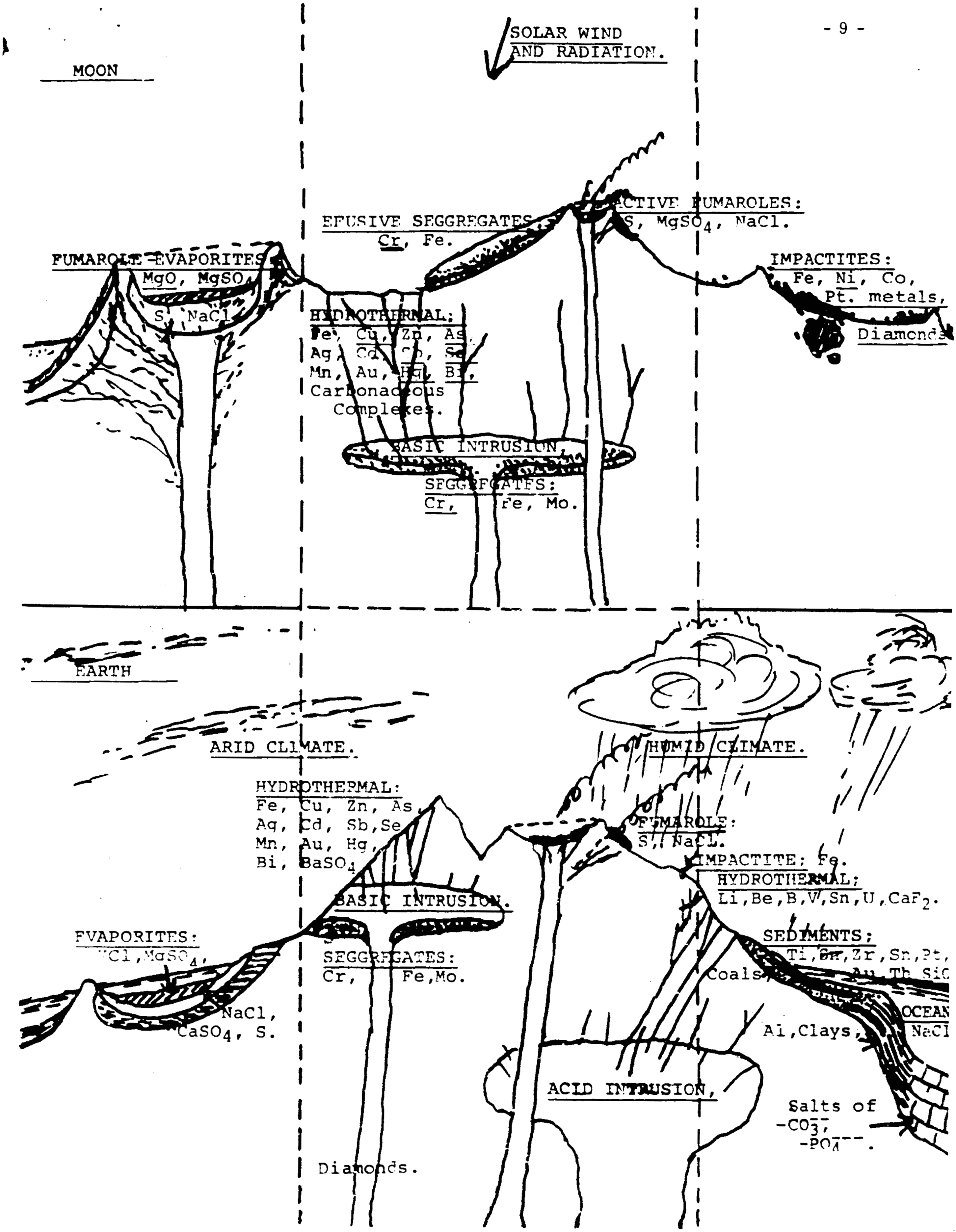
The economic utility of the mineral deposits within the more distant future may primarily depend on the degree of lowering of costs of trips to the Moon, particularly through the advent of the atomic rocket. With the gradual exhaustion of the small number of top grade terrestrial deposits, our mining techniques and metallurgy tend to become more and more adapted toward the exploration of lower grade and more extensive deposits. It may be that a considerable number of top grade deposits, including those of high priced platinum metals, etc., will be found on the surface of the Moon. Another potential economic advantage may be that the lunar deposits may, to some extent, compensate the terrestrial ones, because of the different conditions which prevailed in the course of their genesis. For example, the mainly NaCl-containing evaporite deposits of the Earth may be compensated by the predominantly magnesian deposits of the Moon.

Our schematical diagram illustrates the geological settings of the main genetical types of terrestrial and the conjectural lunar deposits. Within the central division of the illustration, those genetical types of deposits are shown, which may exist both on the Moon and on our planet, according to the theoretical considerations made in the present comparative studies. The left and right extremities of the diagram show those lunar deposits, which have no clear terrestrial genetical parallel, and vice-versa.

Finally, the writer ventures to present a table which compares the volume and grade of possible lunar deposits of the more important metals and non-metallic minerals, with their terrestrial genetical equivalents or quasi-equivalents.

GENETICAL TYPE OF LUNAR DEPOSIT

Volume and grade, compared to similar terrestrial deposits	Magmatic Segreg.	Fumarole-Evaporite	Hydro-thermal	Sedimentary	Carbo-naceous	Impactite
SUPERIOR	Cr	$MgSO_4$	As, Sb, Se, Bi, Hg	-	Graphite, Graphitite	Fe, Co, Ni, Pt. metals, Diamonds
EQUAL	Fe	$CaSO_4$ $CaCO_3$	Cu, Zn, Ag, Cd, Mn, Au	-	Abioliths	-
INFERIOR	-	S, NaCl, KCl	Pb, $BaSO_4$, Phosphate	-	-	-
VERY INFERIOR OR NON-EXISTENT	Diamonds	-	Li, Be, B, Ti, V, Nb, Mo, Sn, Rare Earths, Ta, U, CaF_2	Al, Mn, Fe, Ti, Zr, Sn, Pt. metals, Au, Clays, Phosphate, $CaCO_3$, SiO_2, Corundum, Garnet	Coals, Oil, Asphalts, Gas	-


MOON
SOLAR WIND AND RADIATION.
FUMAROLE EVAPORITES: MgO, MgSO4, S, NaCl
EFUSIVE SEGGREGATES: Cr, Fe.
ACTIVE FUMAROLES: S, MgSO4, NaCl.
IMPACTITES: Fe, Ni, Co, Pt. metals, Diamonds
HYDROTHERMAL: Fe, Cu, Zn, As, Ag, Cd, Sb, Se, Mn, Au, Hg, Bi, Carbonaceous Complexes.
BASIC INTRUSION, SEGGREGATES: Cr, Fe, Mo.
EARTH
ARID CLIMATE.
HUMID CLIMATE.
HYDROTHERMAL: Fe, Cu, Zn, As, Ag, Cd, Sb, Se, Mn, Au, Hg, Bi, BaSO4
FUMAROLE: S, NaCL.
IMPACTITE; Fe.
HYDROTHERMAL; Li, Be, B, V, Sn, U, CaF2.
BASIC INTRUSION.
EVAPORITES: NaCl, CaSO4, S.
SEGGREGATES: Cr, Fe, Mo.
SEDIMENTS; Ti, Zr, Sn, Pt, Au, Th SiC
Coals,
OCEAN NaCl
Al, Clays,
ACID INTRUSION,
Salts of -CO3--, -PO4---.
Diamonds.

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REFERENCES

1. Bateman, A. M., "The Formation of Mineral Deposits." John Wiley and Sons, New York (1951).

2. Riley, Ch. M., "Our Mineral Resources." John Wiley and Sons, New York (1959).

3. Mueller, G., Trans. New York Acad. Sci, Ser. II, 23, 735-753 (1961).

4. Mueller, G., Nature, 211, 1134-1135 (1966).

5. Heacock, R. L. et al., Technical Report No. 32-700, NASA (1965).

6. Mueller, G. and Veryl, Ch., Proc. XXth Int. Geol. Congress, Mexico, 1, 375-396 (1957).

7. Kuiper, G. P., Technical Report No. 32-700, NASA, pp. 9-73.

8. Mueller, G., Nature, 196, 929-932 (1962).

9. Mueller, G., Proc. VIth World Petroleum Congress, Frankfurt-am-Main, Sect. I, 1-14 (1963).

10. Wilson, A. T., Nature, 195, 12 (1962).